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Relationships of Field Habitat Measurements, Visual Habitat Indices, and Land Cover to Benthic Macroinvertebrates in Urbanized Streams of the Santa Clara Valley, California

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Abstract.—We evaluated several approaches for measuring natural and anthropogenic habitat characteristics to predict benthic macroinvertebrate assemblages over a range of urban intensity at 85 stream sites in the Santa Clara Valley, California. Land cover was summarized as percentage urban land cover and impervious area within upstream buffers and the upstream subwatersheds. Field measurements characterized water chemistry, channel slope, sediment, and riparian canopy. In addition to applying the visual-based habitat assessment in U.S. Environmental Protection Agency's rapid bioassessment protocol, we developed a simplified urban habitat assessment index based on turbidity, fine sediment deposition, riparian condition, and channel modification. Natural and anthropogenic habitat variables covaried along longitudinal stream gradients and were highly correlated with elevation. At the scale of the entire watershed, benthic macroinvertebrate measures were equally correlated with variables expressing natural gradients and urbanization effects. When natural gradients were reduced by partitioning sites into ecoregion subsection groupings, habitat variables most highly correlated with macroinvertebrate measures differed between upland and valley floor site groups. Among the valley floor sites, channel slope and physical modification of channel and riparian habitats appeared more important than upstream land cover or water quality in determining macroinvertebrate richness and ordination scores. Among upland sites, effects of upstream reservoir releases on habitat quality appeared important. Rapid habitat evaluation methods appeared to be an effective method for describing habitat features important to benthic macroinvertebrates when adapted for the region and the disturbance of interest.

Introduction

Biological sampling protocols for water quality assessment usually include habitat measurements. Habitat information is commonly used to predict an expected (unimpaired) condition that can be used for comparison with potentially impaired sites. One approach is to designate reference (unimpaired) sites (e.g., Hughes et al. 1986) based in part on the quality of local habitat conditions. At a large spatial scale, programs may use habitat measurements from many reference sites to develop models that predict biota on the basis of habitat characteristics (e.g., Wright 1995). Habitat measurements such as amount of urban land cover (e.g., Kennen 1999; Morley and Karr 2002) or local habitat structure (e.g., Robinson and Minshall 1998; Barbour et al. 1999; Beavan et al. 2001) may also be used as a direct measure of anthropogenic disturbance.

Habitat variables used in bioassessment protocols usually include a combination of landscape measurements and field observations (Fitzpatrick et al. 1998; Barbour et al. 1999). Landscape variables such as land cover and watershed morphology are typically calculated using maps, photographs, and geographical information systems data. Field observations can be direct measurements, visual estimates or expert evaluation. Field measurements can be standardized and often have good statistical properties, but have the disadvantage of being relatively time-consuming to acquire at the appropriate spatial/temporal scale. To

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reduce costs, alternative habitat scoring approaches have been developed, such as the visual-based habitat assessment (VBHA) in the U.S. Environmental Protection Agency's rapid bioassessment protocol (Barbour et al. 1999). The VBHA and similar approaches are usually standardized using ordinal scores based on explicitly defined categories.

The list of potential habitat effects on aquatic biota is extensive, and cost constraints make selection of habitat measurements an important component of bioassessment study design. Selection of appropriate measurements may be particularly difficult in urbanized stream systems, which are characterized by novel habitat modifications that may differ greatly among watersheds or regions. Recent approaches to regional prediction of biota using habitat characteristics often have emphasized habitats with minimal anthropogenic modifications (Wright 1995; Hawkins et al. 2000; Weigel et al. 2003). Nevertheless, many areas have become so extensively modified that it has become difficult to identify unimpaired sites (Hughes 1995; Yoder and Rankin 1995; Alba-Tercedor and Pujante 2000).

Our purpose was to determine which habitat features and measurement techniques were most useful in predicting the biological condition of stream reaches in an urbanized watershed. We evaluated data from a survey of streams in the Santa Clara Valley, California, by correlating a wide range of habitat variables with benthic macroinvertebrate scores. Much of the valley is urbanized; therefore, both natural and anthropogenic factors were assumed to be important. Rather than using predetermined categories (e.g., test versus reference) based on either habitat quality or macroinvertebrate measures, we considered both to be continuous. We sampled the area at a high density to account for both large-scale patterns and the possibility of local habitat effects on macroinvertebrates.

Study Area

Streams within the Santa Clara Valley (SCV) drain northward into south San Francisco Bay in central California, USA (Figure 1). The SCV is located between the northwest-trending Santa Cruz Mountains to the west and the Diablo Range to the east. The total watershed area is approximately 1,600 km^2, and maximum elevations are about 1,000 m. The climate is Mediterranean, with almost no rainfall from May to October. Historically, many of the streams in the SCV

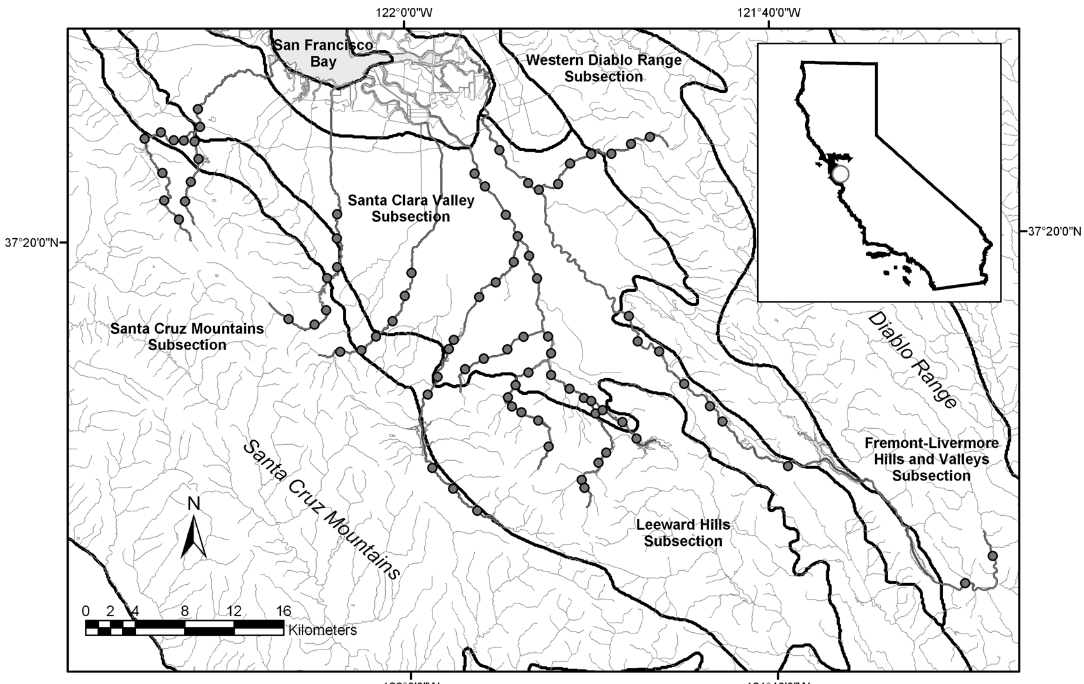


FIGURE 1. Map of the Santa Clara Valley, showing streams (gray lines), collection sites, and ecoregion subsection boundaries (dark lines). Inset shows location on California map.

were dry during the summer (Santa Clara Basin Watershed Management Initiative 2001), but now most mid to lower reaches are intensively managed by storage reservoirs and are augmented by water imported from outside the watershed. Consequently, flow regime in the SCV is highly modified, and many formerly intermittent reaches are now perennial.

Santa Clara Valley watersheds occupy portions of two ecoregions (provinces), which are divided into sections and subsections by Miles and Goudey (1997). The valley floor corresponds to the Santa Clara Valley subsection of the California Coastal Chaparral Forest and Shrub Province and is mostly located on gently sloping floodplain and alluvial fans of Late Quaternary origin. Predisturbance vegetation was mostly grasslands and oaks, but much of this subsection is now dominated by urban and more limited agricultural land cover. The western slopes include portions of two subsections, both of which are largely forested: the Santa Cruz Mountains and the Leeward Hills. The Leeward Hills subsection is underlain primarily by metamorphosed sediments and volcanics of the Franciscan Complex, and the Santa Cruz Mountains subsection is primarily a mix of Mesozoic and Tertiary marine sedimentary rock (Miles and Goudey 1997). The eastern slopes include portions of the Fremont-Livermore Hills and Valleys subsection and the Western Diablo Range subsection, which are at the northwestern edge of the California Coastal Range Shrub-Forest-Meadow Province. This part of the watershed is more xeric, dominated by grasslands, chaparral, and oak-savanna, and the sampled areas are dominated by Franciscan Complex rocks. Upland areas of both the eastern and western slopes are mostly nonurban.

Methods

Study Design

We sampled near-perennial reaches of 14 streams throughout the watershed at 2-km intervals, within constraints of accessibility, available riffle habitat, and an approximately 300-m upper elevation limit. Reach length was variable (30–175 m, median = 70 m) and generally included at least two riffle-pool sequences.

The relationship between macroinvertebrates and habitat was evaluated by correlation. Two spatial scales were considered: the watershed scale (entire data set of 85 sites), and the ecoregion subsection scale. Because five upland sites on the east slope are in a different ecoregion province, they were used only in the watershed-scale analyses and were omitted from the ecoregion subsection analyses (N = 80). The subsection analyses were done separately for valley sites (the valley floor; within the Santa Clara Valley subsection; N = 46) and upland sites (the western slope; combined Santa Cruz Mountain and Leeward Hills subsections; N = 34). Although there was substantial overlap, the division between valley and upland site groups corresponds approximately to the 100 m elevation contour.

Macroinvertebrate Samples

Benthic macroinvertebrates were collected in riffle habitat at 85 sites during May 1997 (Carter and Fend 2000), which was a period of declining flow in natural streams. Each collection was a composite of 5–0.1-m^2 kick samples taken with a 0.3-m-wide D-frame kicknet fitted with a 500-mm mesh. The five individual kick samples were collected systematically in each riffle in a downstream to upstream direction, crossing the stream twice along two diagonal lines (i.e., a V-shape across the riffle's breadth). Two of the five samples were obtained in the thalweg, and the remaining three samples were taken between the thalweg and the margins. At sites containing long riffles, sampling focused on the upstream portion of the riffle. The composited collection was preserved in the field with 10% buffered formalin. Each composited collection was subsampled to a target of 500 organisms (Moulton et al. 2000), sorted at 8× magnification, and invertebrate counts scaled to the estimated 0.5-m^2 total. The remainder of the sample was sorted without magnification for large, rare organisms that may have been missed during the subsampling process (Moulton et al. 2000), and these were added to the total. All macroinvertebrates were identified to the lowest practical taxonomic level (Moulton et al. 2000); in most cases, to species or genus.

Habitat Measurements

A wide range of habitat data were obtained for each macroinvertebrate collection site. Habitat measures were limited to those requiring minimal field time or readily available from other sources. These were grouped according to spatial measurement scale and general approach: landscape measurements, field measurements, and field visual estimates (Table 1).

Landscape measurements.—Following determination of spatial coordinates in the field using a Global Positioning System receiver, a stream segment was identified for each site on a 1:24,000-scale U.S. Geological

TABLE 1. Definitions and abbreviations of habitat variables used in the analyses. Medians and ranges of values for the entire Santa Clara Valley watershed (all sites) and for the two site groups defined by ecoregion subsections (see text). VBHA scores refer to the visual-based habitat assessment protocol (Barbour 1999).

		All sites (N = 85)		Valley sites (N = 46)		Upland sites (west slope) (N = 34)	
Abbreviation	Variable definition	Median	Range	Median	Range	Median	Range
	Landscape variables						
ELEV	Site elevation (m)	82	8–341	56	8–110	134	55–299
AREA	Subwatershed area upstream of site (km²)	49	5–824	105	8–824	25	5–102
DFM	Distance to mouth of stream at SF Bay (km)	25.0	7.1–79.8	23.7	7.1–53.1	25.8	13.8–41.7
DAMDIST	Distance to nearest upstream dam (km) (undammed = 50 km)	10.4	0.3–50	11.0	0.6–50	6.0	0.3–50
SLOPEMAP	Slope (%), derived from map contours	0.6	0.2–12	0.50	0.2–3.5	2.0	0.4–6
BUFURB	% urban land cover in 200 m × 2 km, upstream buffer	36	0–96	71	4–96	4	0–77
BUFNURB	% nonurban, nonagricultural land cover in upstream buffer	34	3–100	13	3–82	86	23–100
BUFPIA	% impervious area in upstream buffer	25	1–74	42	4–74	3	1–44
AREAURB	% urban land cover in subwatershed	5	0–70	11	1–70	2	0–19
AREANURB	% nonurban, nonagricultural land cover in subwatershed	92	26–100	84	26–98	97	79–100
AREAPIA	% impervious area in subwatershed	4	1–40	8	2–40	2.1	1–12
RDDENS	Road density in subwatershed, m/ha	26	9–96	30	13–96	25	9–46
	Field measurements						
SLOPERIF	Slope (%), field measurement of sampled riffle	1.70	0.04–6.27	1.27	0.11–4.17	2.35	0.04–6.08
SLOPERCH	Slope (%), field measurement of sampled reach	0.83	0.11–4.70	0.64	0.11–1.34	1.35	0.34–3.62
WWIDTH	Riffle wetted width (m) (mean of 3)	4.3	1.2–12.2	4.6	1.5–12.2	3.8	1.8–9.8
RDEPTH	Riffle depth (cm) (mean of 5)	12.8	4.6–24.4	14.3	4.6–24.4	12.2	5.5–20.7
RVELOC	Riffle velocity (m/s) (mean of 5)	0.43	0.15–0.98	0.44	0.15–0.98	0.41	0.2–0.68
EMBED	Sediment embeddedness, mean % depth of 10 rocks	26	0–60	27	9–47	22	0–60
16%PS	16th percentile particle size (mm), riffle sediment	21	1–71	18	9–48	20	1–60
50%PS	50th percentile particle size (mm), riffle sediment	57	12–130	50	19–130	66	12–120
84%PS	84th percentile particle size (mm), riffle sediment	120	22–270	104	31–270	138	22–240
SEDSORT	Sediment sorting coefficient	2.1	1.5–6.9	2.1	1.5–4.3	2.4	1.5–6.9
CANOPY	% open canopy (mean of 3)	30	3–100	60	5–100	11	3–92
DO	Dissolved oxygen, percent saturation	101	50–178	109	50–178	98	66–116
COND	Specific conductance (µS)	546	272–1277	554	296–1,277	458	272–853
PH	pH	8.2	7.2–9.3	8.3	7.5–9.3	8.1	7.2–8.5
TEMP	Water temperature, °C	18.5	10.7–30.3	20.2	14.1–30.3	15.5	10.7–21.6
NO3	Nitrate + nitrite nitrogen (µg/L)	175	0–5,884	268	0–5,884	136	2–3,557
PO4	Phosphate phosphorus (µg/L)	28.9	0.2–289	28.4	0.6–289	30.0	0.5–210
NH4	Ammonia (µg/L)	0.50	0–616	0.58	0–200	0.34	0-616

TABLE 1. Continued.

Abbreviation	Variable definition	All sites (N = 85)		Valley sites (N = 46)		Upland sites (west slope) (N = 34)	
		Median	Range	Median	Range	Median	Range
Al	Aluminum (µg/L)	1.36	0.30–12.80	1.49	0.43–5.86	1.13	0.30-12.80
V	Vanadium (µg/L)	1.60	0.28–4.10	2.12	0.56–4.10	1.32	0.28-3.82
Cr	Chromium (µg/L)	0.5	0–53.2	0.6	0.1–53.2	0.4	0-42.9
Mn	Manganese (µg/L)	3.6	0.2–2,868	3.0	0.3–69.8	4.8	0.2-2868
Fe	Iron (µg/L)	95	15–221	85	15–221	132	23-208
Co	Cobalt (µg/L)	0.09	0.03–0.56	0.09	0.03–0.26	0.10	0.03-0.56
Ni	Nickel (µg/L)	2.5	0.03–13.5	2.7	0.48–5.0	2.3	0.03-13.5
Zn	Zinc (µg/L)	22.8	3.9–45.2	22.2	5.1–32.5	22.6	3.9–45.2
Cu	Copper (µg/L)	0.87	0.23–4.29	1.15	0.28–3.05	0.71	0.23–4.29
Cd	Cadmium (µg/L)	0.006	0.001–0.021	0.006	0.001–0.020	0.005	0.001–0.021
Pb	Lead (µg/L)	0.027	0.009–0.166	0.026	0.010–0.166	0.027	0.009–0.074
	Field visual observations						
VBBSTAB	VBHA bank stability score[b]	12	5–18	14	5–18	11	5–16
VBBVEG	VBHA bank vegetative protection score[b]	13	4–18	13	4–17	14	6–18
VBCHFLO	VBHA channel flow score[b]	13	4–18	15	8–18	11	4–18
VBCHALT	VBHA channel alteration score[b]	13	4–18	12	4–18	13	5–17
VBEMBED	VBHA embeddedness score[b]	14	7–18	13	7–17	14	8–18
VBEPSUB	VBHA epifaunal substrate score[b]	15	6–19	15	8–18	15	6–19
VBRIFFQ	VBHA riffle frequency score[b]	11	4–18	10	6–17	13	5–17
VBRIPZW	VBHA riparian zone width score[b]	12	2–18	10	2–17	15	6–18
VBSEDDP	VBHA sediment deposition score[b]	12	5–17	11	5–17	13	5–17
VBVELDP	VBHA velocity-depth regime score[b]	14	4–18	13	4–18	15	4–18
VBTOT	VBHA combined index score	130	69–161	129	69–161	132	103–151
ALGCOVR	Algal cover score (0–4 scale)	1	0–4	2	0–4	0	0–4
SILT	Benthic silt cover score (riffle sediment)[a]	2	1–4	2	1–3.5	1.5	1–3
TURB	Turbidity score (1–3 scale)	1	1–3	2	1–3	1	1–3
CHANMODF	Channel modification score[a]	2	1–4	3	1–4	1.5	1–3.5
RIPVEG	Riparian vegetation composition score[a]	2	1–4	3	1.5–4	1	1–3.5
RIPW	Riparian vegetation width score[a]	3	1–4	3	1.5–4	2	1–4
UHA	Urban habitat assessment	2.0	1.1–3.0	2.4	1.5–3.0	1.4	1.1–2.4

[a] 1–4 scale.
[b] 1–20 scale.

Survey topographic map. Stream segments were defined as sections between major tributaries that had relatively constant slope and valley form (Frissell et al. 1986). Segment slope and distance from mouth were determined from map measurements, using a map wheel. Stream order was determined from solid blue map lines according to Strahler (1957).

Watershed boundaries were obtained from the Santa Clara Valley Water District. Topographically defined "subwatersheds" (defined here as the watershed upstream of each sampling site) were hand-digitized using 1:24,000 scale maps to reflect the influence of major stormwater drain systems. National Land Cover Data (NLCD; Vogelmann et al. 2001) at 30-m resolution were used to generate land cover estimates at two spatial measurement scales: (1) 200-m buffer strips (100 m wide on each side), extending 2 km upstream; and (2) the total subwatershed upstream of each site. Land cover was summarized as percentage urban, percentage nonurban/nonagricultural, and percentage impervious area (PIA). The percentage urban area was the sum of NLCD categories "Low Intensity Residential," "High Intensity Residential," "Commercial/Industrial/Transportation," and "Quarries/Strip Mines/Gravel Pits."

Imperviousness is a common means of weighting the influence of urban land cover on aquatic habitats (Walsh 2000), but sources of data relating it to land cover in the SCV are limited. The NLCD assigns a median total PIA of 90% to high intensity residential and industrial land cover categories and 55% to low intensity residential. Imperviousness for other NLCD land cover categories was estimated as 1% for natural habitats, 2% for agricultural land, and 3% for "Urban/Recreational Grasses" (Appendix 4A-1 in Santa Clara Basin Watershed Management Initiative 2001). As the categories were coarse, our calculated PIA values were assumed to be imprecise and were used in a relative sense. Density (length/area) of paved roads was derived for upstream subwatersheds using data from the California Department of Fish and Game (2002); calculations were based on road length only, due to inconsistencies in width information.

Field measurements.—Temperature, conductivity, pH, and dissolved oxygen were measured at the time of macroinvertebrate sampling (May 1997) and once again during the following month, using handheld meters. Nitrate+nitrite nitrogen was sampled in June 1997 and again in September 1998. Phosphate, ammonia, and selected trace elements were sampled once, in September 1998. Nutrients (nitrate, ammonia, and phosphate) were analyzed by automated spectrophotometry. Dissolved trace elements were determined by direct-injection inductively coupled plasma mass spectrometry using both external and internal standardization. Elements analyzed included aluminum, vanadium, chromium, manganese, iron, cobalt, nickel, zinc, copper, cadmium, and lead.

Physical measurements were made on site, at either the scale of the sample reach or the sampled riffle. Depth and velocity were measured at each macroinvertebrate sample point at the time of macroinvertebrate sampling. Sediment particle size (d) was measured as the length of the second-longest axis and based on a random selection of 100 particles from throughout the riffle sample area (Wolman 1954). Particle size was summarized as the 16th percentile ($d16$), the median ($d50$), and the 84th percentile ($d84$) of the second axis widths. As a measure of sediment heterogeneity, a sorting index (Andrews 1983) was calculated: $1/2(d84/d50+d50/d16)$. Sediment embeddedness was measured as the percentage depth (along the vertical axis) a particle was buried in sand or finer material, and the mean value was based on 10 randomly chosen particles. Water surface slope was measured at low flow over the sampled riffle and for the entire reach, using an auto-level. Riparian canopy shading was measured at three midchannel points within the sample area, using a Solar Pathfinder (Solar Pathways, Inc.) to measure the solar arc for May; the value was expressed as a percentage of the expected insolation.

Field visual observations.—Visual habitat scoring approaches are used in most state bioassessment protocols in the United States (USEPA 2002a). The VBHA in the U.S. Environmental Protection Agency's rapid bioassessment protocol (Barbour et al. 1999) is commonly used and is currently recommended for use in California bioassessments (California Department of Fish and Game 2003). The VBHA scores 10 reach-scale channel features on a 1–20 scale with respect to habitat. The individual scores are summed to calculate the total index score, which can range from 10 (extremely poor) to 200. The VBHA was conducted by a single observer (F. R. Kearns) during June–July 1999 and again in summer 2000 (Kearns 2003), after prior calibration exercises with one of the developers of the protocol (Dr. M. T. Barbour, Tetra-Tech, Inc.). For consistency, all observations were based on the protocol for high gradient streams.

A study-specific Urban Habitat Assessment index (UHA) was devised from descriptive field notes taken during the macroinvertebrate sampling trip.

Categorical observations (Table 2) on a simplified, 1–4 scale were ordered to increase with urban disturbance. The categorical observations were made about one month after the macroinvertebrate collection and postcalibrated with photos. Mean values were assigned for riparian scores when the two stream banks differed and for sediment scores where the value varied over the macroinvertebrate sample reach. Visual estimates of canopy shading and sediment embeddedness were difficult to standardize, so data from the field measurements were converted to a 1–4 linear scale and used in the final calculation. Turbidity was recorded at three levels because of difficulty in standardizing observations at higher turbidity levels; the values were rescaled to a range of 1–4 (i.e., 1, 2.5, 4) for the UHA calculation. The total UHA index score was calculated as the average of these values.

In contrast to the VBHA, values of the UHA increase with urbanization. Cover by filamentous algae in riffle sediments was estimated as an additional, 1–5 visual score, but was not included in the UHA or VBHA.

Analysis Methods

We summarized macroinvertebrate data by calculating two conceptually different scores or metrics. The first, "EPT richness," is the number of species of three orders of insects that are considered sensitive to pollution: Ephemeroptera, Plecoptera, and Trichoptera (EPT). Ephemeroptera, Plecoptera, and Trichoptera richness is used in most macroinvertebrate bioassessments in the United States and almost invariably shows a negative correlation with measures of urban intensity (Kerans and Karr 1994). Because variation in the number of macroinvertebrates sorted has a major effect on estimated richness values, all samples were standardized by randomly resampling the scaled data to 470 organisms (the size of the actual minimum sample). Calculated EPT richness was based on the mean of 100 resamplings. The second biological score was derived from the first axis of a detrended correspondence analysis (DCA) ordination of the macroinvertebrate data, using log-transformed abundance data and the "detrending by segments" option in the PC-ORD software package (McCune and Mefford 1999). Detrended correspondence analysis derives a dominant trend from patterns in macroinvertebrate assemblages, and the resulting site scores are not based on prior assumptions of pollution tolerance. Detrended correspondence analysis ordination was done for the entire watershed and also separately for valley and upland site groups.

Habitat data were initially summarized by principal components analysis (PCA) to show general trends and interrelationships among the variables. For

TABLE 2. Habitat categories used in calculating the urban habitat assessment index (UHA) in Santa Clara Valley streams. Observations were scored 1–4, except for turbidity, which was collapsed to three levels.

	Score value			
Variable	1	2	3	4
Embeddedness, mean % depth of 10 rocks	<25%	25–50%	51–75%	>75%
% open canopy, mean of three measurements	<25%	25–50%	51–75%	>75%
Benthic silt cover (riffle sediment)	no obvious deposits of silt	deposits along stream margins	interstitial silt visible from surface	tops of rocks with visible silt layer
Turbidity	clear	turbid, bottom visible in about 0.3 m depth	turbid, bottom not visible	–
Channel modification	approximately natural channel	small structures: riprap, check dams	dirt or setback levees	v-shaped concrete
Riparian vegetation composition	native plants, nearly natural structure	nonnative, structure similar to natural	nonnative, structure different	very sparse
Riparian vegetation width	>30 m	15–30 m	<15 m	mostly absent

the PCA, percentage data were arcsine square root transformed (Zar 1974) and chemical measurements were $\log_{10}$ transformed. Spearman rank correlation coefficients (r_s) were used to compare the strength of relationships between environmental variables and benthic macroinvertebrate scores. Because of multicolinearity among habitat variables, the correlation coefficients were used as a descriptive measure of relative explanatory value, rather than a measure of significance. Principal components analysis and correlation analyses were performed using STATISTICA 6.0 (StatSoft, Inc. 2004).

Results

Habitat Data

Stream order ranged from 2 to 5 among the 85 sites. Dissolved oxygen was near or above saturation (Table 1); only six below-dam or downstream sites were at or below 80% saturation on the May and June 1997 sampling dates. All sites were circumneutral to slightly alkaline. Daytime water temperatures during May ranged from 11–30°C, but only four sites were greater than 25°C. Similar temperature ranges were observed in June. Concentrations of trace elements (Table 1) were below continuous aquatic life criteria (USEPA 2002b), and only one ammonia measurement was near the criterion. Although ranges of most values overlapped between valley and upland sites (Table 1), median values for nitrate, urban land cover, and variables expressing modification of channel and riparian habitats were higher at valley sites.

The first PCA axis of habitat data for the entire watershed (Table 3) suggested a typical, up- to downstream longitudinal gradient (e.g., Hawkes 1975). Variables such as channel slope (SLOPEMAP, SLOPERCH), sediment particle size (84%PS), and nonurban land use (BUFNURB, AREANURB) were associated with higher site elevation (ELEV). Lower elevation sites were associated with increased temperature (TEMP), canopy opening (CANOPY), urban land use (e.g., AREAURB, BUFPIA, RDDENS), and local habitat modification (CHANMODF, RIPVEG, RIPW). Consequently, it did not appear possible to separate effects of urbanization from natural, longitudinal/elevation gradients when evaluating the entire watershed.

Several water chemistry variables, including phosphate, conductivity, and trace elements (Fe, Co, Cd, and Pb), were negatively associated with the second PCA axis, suggesting that they were not entirely a function of our measures of land cover or the dominant up- to downstream habitat gradient. Distance to the nearest upstream dam (DAMDIST) also was negatively associated with the second axis, but some visual measures of habitat quality (VBBSTAB, VBCHFLO) had positive loadings.

Principal components analysis results for the valley and upland site groups differed somewhat from those for the entire watershed (Table 3). Axis 1 of the valley site group PCA indicated an association between urban land cover and categorical observations of habitat modification (positive loadings for VBBVEG, VBCHALT, VBEPSUB, VBRIPZW, and VBVELDP; negative for CHANMODF and RIPW). Axis 2 showed a negative relationship between elevation and most dissolved constituents. In the upland site group, axis 1 associated subwatershed urban land cover (AREAURB) with most of the dissolved constituents (all had negative loadings). Axis 2 negatively associated upland sites not influenced by upstream dams (ELEV, DAMDIST) with ammonia, manganese, algal cover, silt, turbidity, and decreased pH.

Macroinvertebrate Data

The median total richness (number of taxa in a 470-count subsample) per site was 48.5 (range = 30.2–72); median EPT richness was 10.5 (2.7–26.5). Widespread EPT taxa present in over half of the samples included the ephemeropterans *Baetis tricaudatus* and *Tricorythodes minutus*, the plecopteran *Malenka californica*, and the trichopterans *Hydropsyche californica* and *Hydroptila*. The median percentage of individuals per site that were EPT taxa was 34.8% (range = 1.3–78.4). Ephemeroptera, Plecoptera, and Trichoptera abundance was dominated by two families considered relatively tolerant to pollutants (California Department of Fish and Game 2003), the Baetidae (Ephemeroptera) and Hydropsychidae (Trichoptera). The median percentage abundance represented by Baetidae was 15.7% (0–60.8%); that of the filter feeding Hydropsychidae was 3.4% (0–46.7%). For the entire data set, numerically dominant (greater than 1% of the total abundance) EPT taxa were the ephemeropterans *B. tricaudatus*, *Fallceon quilleri* and *Diphetor hageni*, the plecopteran *M. californica*, and the trichopterans *H. californica* and *Cheumatopsyche mickeli*. Other numerically dominant taxa included members of the dipteran families Simuliidae (four *Simulium* species) and Chironomidae (seven species), and the oligochaete family Naididae (five species).

TABLE 3. Factor loadings of original variables on the first two axes from principal components analysis of habitat variables measured in Santa Clara Valley streams. Separate analyses were done for the entire data set and for the two site groups. Only variables with at least one loading ≥ |0.5| are shown; loadings ≥ |0.5| are in bold. The total VBHA and UHA scores were not included, as they are linear combinations of other variables. Abbreviations for variables as in Table 1.

	All sites (N = 85)		Valley sites (N = 46)		Upland sites (west slope) (N = 34)	
Habitat variable	Factor 1	Factor 2	Factor 1	Factor 2	Factor 1	Factor 2
Landscape variables						
ELEV	**0.79**	–0.19	0.31	**–0.66**	0.40	**0.73**
AREA	–0.29	0.23	0.41	**0.53**	–0.16	**–0.55**
DFM	0.46	0.45	**0.50**	**–0.51**	**0.77**	0.01
DAMDIST	–0.06	**–0.52**	**–0.67**	0.29	–0.27	**0.80**
SLOPEMAP	**0.60**	–0.37	0.16	–0.14	0.19	**0.65**
BUFURB	**–0.80**	0.04	**–0.61**	0.04	–0.29	–0.31
BUFNURB	**0.86**	–0.12	**0.63**	–0.13	0.39	**0.68**
BUFPIA	**–0.82**	0.04	**–0.56**	0.21	–0.31	–0.29
AREAURB	**–0.85**	–0.29	**–0.90**	0.18	**–0.89**	–0.22
AREANURB	**0.88**	0.20	**0.86**	–0.20	**0.86**	0.38
AREAPIA	**–0.85**	–0.30	**–0.89**	0.22	**–0.89**	–0.21
RDDENS	**–0.69**	–0.44	**–0.90**	0.11	**–0.87**	0.04
Field measurements						
SLOPERCH	**0.63**	–0.42	0.29	–0.16	0.06	**0.70**
RDEPTH	–0.16	0.45	0.24	0.10	**0.52**	–0.20
CANOPY	**–0.57**	0.43	–0.23	–0.27	0.07	–0.37
COND	–0.25	**–0.55**	–0.05	**0.70**	**–0.91**	0.19
pH	–0.41	–0.01	**–0.64**	–0.43	–0.11	**0.53**
TEMP	**–0.67**	0.05	**–0.54**	0.00	**–0.56**	–0.19
NO3	–0.25	–0.32	0.06	**0.65**	–0.40	0.03
PO4	–0.26	**–0.69**	–0.49	0.29	**–0.69**	0.20
NH4	–0.11	–0.19	–0.27	0.27	–0.18	**–0.57**
V	**–0.56**	–0.33	–0.23	**0.62**	–0.45	0.21
Mn	0.03	–0.22	0.35	**0.77**	–0.45	**–0.59**
Fe	0.17	**–0.62**	0.37	**0.73**	**–0.72**	0.25
Co	–0.07	**–0.51**	0.37	**0.86**	**–0.77**	–0.14
Ni	0.01	0.03	**0.64**	**0.51**	–0.19	–0.40
Cu	–0.30	–0.38	0.05	**0.62**	**–0.58**	0.13
Cd	–0.34	**–0.68**	–0.33	**0.69**	**–0.80**	0.20
Pb	–0.30	**–0.56**	–0.11	**0.82**	**–0.62**	0.50
Field visual observations						
VBBSTAB	0.08	**0.51**	0.49	0.02	0.49	–0.08
VBBVEG	0.34	0.43	**0.73**	0.17	0.30	–0.28
VBCHFLO	–0.29	**0.52**	0.36	–0.04	0.49	–0.34
VBCHALT	0.41	0.26	**0.74**	–0.03	0.03	–0.03
VBEPSUB	0.40	0.14	**0.59**	0.09	0.05	0.19
VBRIFFQ	0.42	–0.26	0.25	–0.22	0.02	**0.59**
VBRIPZW	**0.69**	–0.10	**0.70**	0.25	0.00	0.14
VBVELDP	0.42	0.07	**0.64**	–0.17	–0.04	0.08
ALGCOVR	–0.39	0.38	–0.08	–0.25	0.11	**–0.62**
SILT	–0.32	0.07	–0.03	0.11	–0.13	**–0.68**
TURB	–0.12	0.40	0.31	0.41	**0.56**	**–0.66**
CHANMODF	**–0.73**	0.14	**–0.52**	0.11	–0.08	–0.12
RIPVEG	**–0.79**	0.22	–0.46	0.08	–0.02	–0.41
RIPW	**–0.75**	0.13	**–0.64**	0.16	–0.01	–0.39

The first DCA axis of the macroinvertebrate data for all 85 sites was clearly dominant (eigenvalue = 0.354 versus 0.090 and 0.071 for axes 2 and 3, respectively). In terms of the taxonomic assemblage, axis 1 was consistent with a gradient of increasing impairment: nearly half (34 of 70) of the EPT taxa had ordination scores in the upper quartile, whereas only three EPT taxa were in the lowest quartile. Relative to other ephemeropterans, the latter taxa (*F. quilleri*, *Callibaetis* sp., and *Caenis* sp.) have been associated with warmer, more polluted, or less erosional conditions (Edmunds et al. 1976; Leland and Fend 1998). Most of the abundant or widespread EPT taxa had intermediate DCA taxon scores.

Macroinvertebrate Scores versus Habitat Data

Landscape data.—At the watershed scale (all 85 sites), EPT richness and DCA axis 1 were highly correlated with elevation (Table 4). This relationship appeared continuous, although not entirely linear (Figures 2A, B). The reduced, but still significant correlation between elevation and macroinvertebrate scores within both upland and valley site groups (Table 4; Figures 3A, B) indicated the importance of natural environmental gradients even over a small elevation range. Segment slope, which was also related to longitudinal stream gradient (r_s = 0.73 for SLOPEMAP

TABLE 4. Correlation coefficients (Spearman r_s) for habitat variables versus EPT S (number of Ephemeroptera, Plecoptera, and Trichoptera taxa) and DCA 1 (axis 1 of detrended correspondence analysis of macroinvertebrate data), from Santa Clara Valley streams. Separate results are given for the entire data set and the two site groups. Only values where $P \leq 0.05$ are shown; r_s values $\geq |0.5|$ are in bold. For consistency, polarity of DCA axis 1 scores was reversed for the valley and upland sites. Abbreviations for variables as in Table 1.

	All sites (*N* = 85)		Valley sites (*N* = 46)		Upland sites (west slope) (*N* = 34)	
Habitat variable	EPT S	DCA 1	EPT S	DCA 1	EPT S	DCA 1
Landscape variables						
ELEV	**0.66**	**0.75**	0.30	0.49	0.39	**0.66**
AREA	**–0.53**	**–0.61**	–0.33	–0.45	–0.34	–0.46
DAMDIST	–	–	–0.40	–0.42	**0.65**	**0.77**
SLOPEMAP	**0.71**	**0.82**	**0.53**	**0.66**	0.42	**0.65**
BUFURB	**–0.50**	**–0.51**	–	–	–	–
BUFNURB	**0.66**	**0.68**	–	–	**0.58**	**0.66**
BUFPIA	**–0.53**	**–0.56**	–	–	–	–
AREAURB	**–0.52**	–0.46	–0.39	–0.34	–	–
AREANURB	**0.65**	**0.62**	0.43	0.38	**0.52**	0.40
AREAPIA	**–0.55**	**–0.50**	–0.39	–0.34	–0.36	
RDDENS	–0.31	–	–0.33	–	–	–
Field measurements						
SLOPERIF	0.36	0.46	–		–	–
SLOPERCH	**0.57**	**0.69**	–	0.47	–	–
WWIDTH	–	–0.27	–	–	–	–
RDEPTH	–0.27	–0.34	–	–	–	–
RVELOC	–0.25	–0.30	–	–0.42	–	–
EMBED	–	–	–	–	–	0.34
16%PS	0.25	–	0.38	–	–	–
50%PS	0.44	0.40	**0.55**	0.49	–	–
84%PS	**0.50**	**0.50**	**0.54**	**0.56**	–	–
SEDSORT	0.24	0.25	0.29	0.38	–	–
CANOPY	**–0.55**	**–0.64**	–0.34	–0.45	–	–
DO	–0.33	–0.37	–	–	–	–
pH	–	–	–	–	**0.66**	**0.57**
TEMP	**–0.52**	**–0.62**	–	**–0.52**	–	–
NO3	–0.23	–	–0.32		–	–

TABLE 4. Continued.

	All sites (N = 85)		Valley sites (N = 46)		Upland sites (west slope) (N = 34)	
Habitat variable	EPT S	DCA 1	EPT S	DCA 1	EPT S	DCA 1
NH4	–0.29	–	–	–	**–0.60**	**–0.60**
Al	–	–	–	–	–	0.43
V	**–0.50**	–0.47	–	–	–	–
Mn	–	–	–	–	**–0.69**	**–0.57**
Fe	–	0.25	–	–	–	–
Co	–	–	–	–	**–0.56**	–0.37
Field visual observations						
VBCHFLO	–0.41	**–0.52**	–	–		
VBCHALT	–	–	0.32	–	–	–
VBEMBED	0.24	–	–	–	–	–
VBRIFFQ	0.35	0.48	–	–	–	0.43
VBRIPZW	0.45	0.48	–	–	–	–
VBSEDDP	0.38	0.30	–	–	**0.54**	0.36
VBVELDP	0.27	0.25	–	–	–	–
VBTOT	0.22	–	–	–	–	–
ALGCOVR	–0.47	**–0.56**	–	–	**–0.57**	**–0.75**
SILT	–0.38	–0.46	–	–	–0.42	**–0.75**
TURB	–0.35	–0.42	–	–0.32	–0.40	**–0.58**
CHANMODF	**–0.58**	**–0.62**	–0.36	**–0.55**	–	–
RIPVEG	**–0.66**	**–0.79**	–0.32	**–0.63**	–	–
RIPW	**–0.58**	**–0.67**	–0.31	**–0.50**	–0.37	–0.46
UHA	**–0.73**	**–0.86**	–0.48	**–0.78**	**–0.53**	**–0.57**

versus ELEV), was also correlated with macroinvertebrate scores at the watershed scale and within the two site groups (Table 4).

Distance to the nearest upstream dam (DAMDIST) was highly correlated with macroinvertebrate measures within the upland site group, where most of the dams occurred (Table 4). In contrast, DAMDIST was negatively correlated with the same measures within the valley site group. In the upland site group, the exclusion of sites within 2 km of an upstream dam increased the correlations (r_s) between elevation and EPT richness from 0.39 to 0.52, and DCA axis 1 from 0.66 to 0.84 (Figures 4A, B).

Buffer and subwatershed land cover variables were highly correlated with macroinvertebrate measures over the entire SCV watershed, but less so within the valley and upland site groups (Table 4). In the entire watershed and within the upland site group, percentage nonurban/nonagricultural land (BUFNURB, AREANURB) was more highly correlated with macroinvertebrates than were percentage urban land cover (BUFURB, AREAURB), PIA or road density (RDDENS) (Table 4; Figures 2C, D, 3C, D). Correlations based on land cover in buffer strips were similar to those based on upstream subwatersheds (Table 4), except in the valley site group, where macroinvertebrate measures were more highly correlated with subwatershed land cover.

Field measurements.—Most water chemistry measurements were weakly correlated with biological variables (Table 4). Exceptions were mostly in the upland site group, suggesting that decreased pH and/or high levels of some trace elements had some effect on biota at below-dam sites. Ammonia concentrations were high (greater than 100 μg/L) at four sites immediately below dams. Temperature, although derived from a single field measurement, was correlated with macroinvertebrates at the watershed scale (Table 4), due to the long elevation gradient.

Channel slope measured over the sample reach

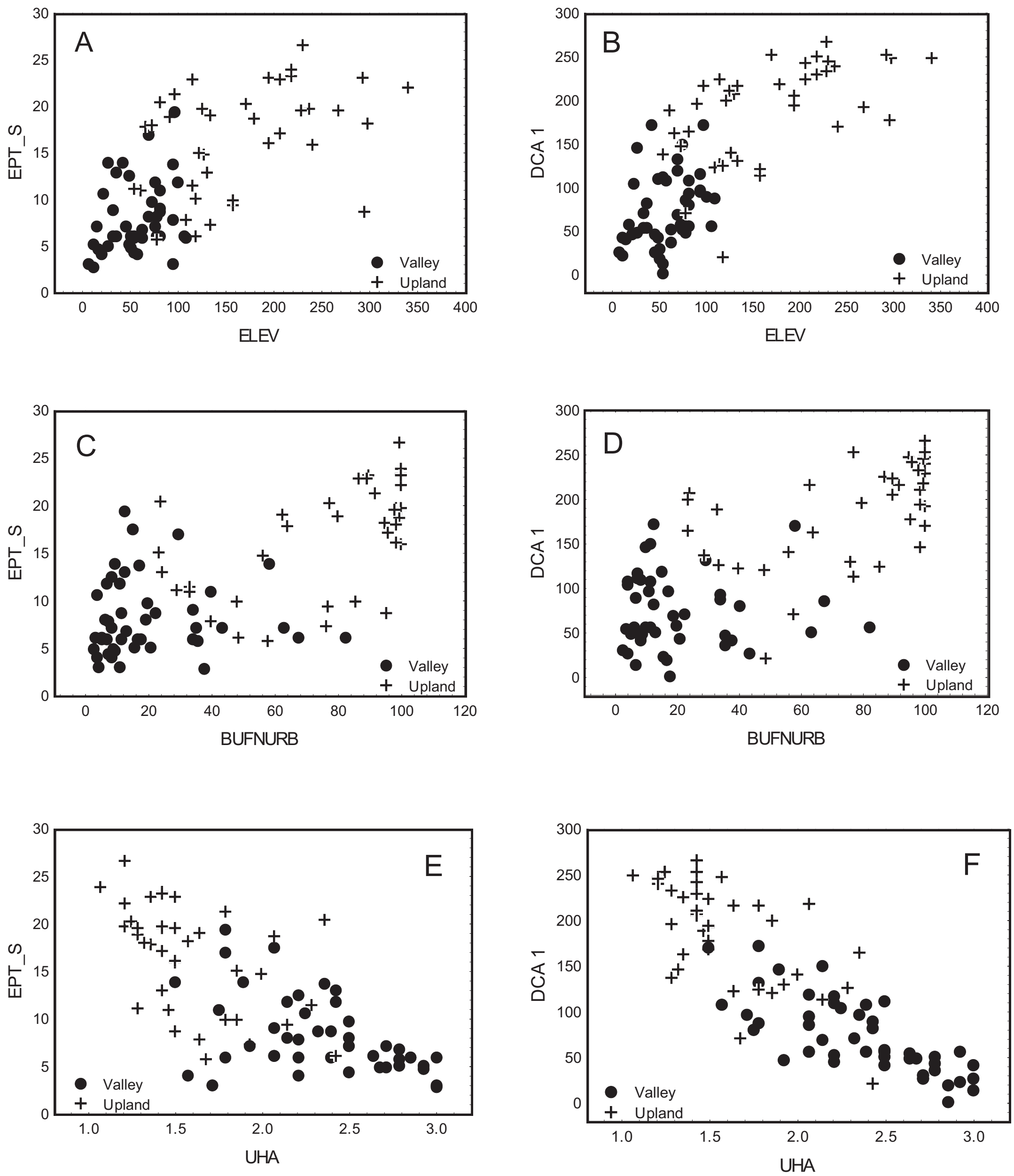


FIGURE 2. Plots of macroinvertebrate variables against habitat variables for all Santa Clara Valley streams. Definitions of variables: EPT S (number of Ephemeroptera, Plecoptera, and Trichoptera taxa), DCA 1 (axis 1 from a detrended correspondence analysis of macroinvertebrate data × 100), ELEV (site elevation in meters), BUFNURB (percent nonurban, nonagricultural land cover in 200 m by 2 km upstream buffers), and UHA (urban habitat index, see Table 2).

(SLOPERCH) was more highly correlated with macroinvertebrate scores than was the slope of the sample riffle (SLOPERIF), but not as highly as the map-derived segment slope (SLOPEMAP) (Table 4). Most other on-site, physical measurements were weakly correlated with macroinvertebrate scores. Riffle sediment measurements were only moderately correlated with the macroinvertebrate variables. Among sediment variables, the 84th percentile particle size (84%PS) usually had higher correlations than the

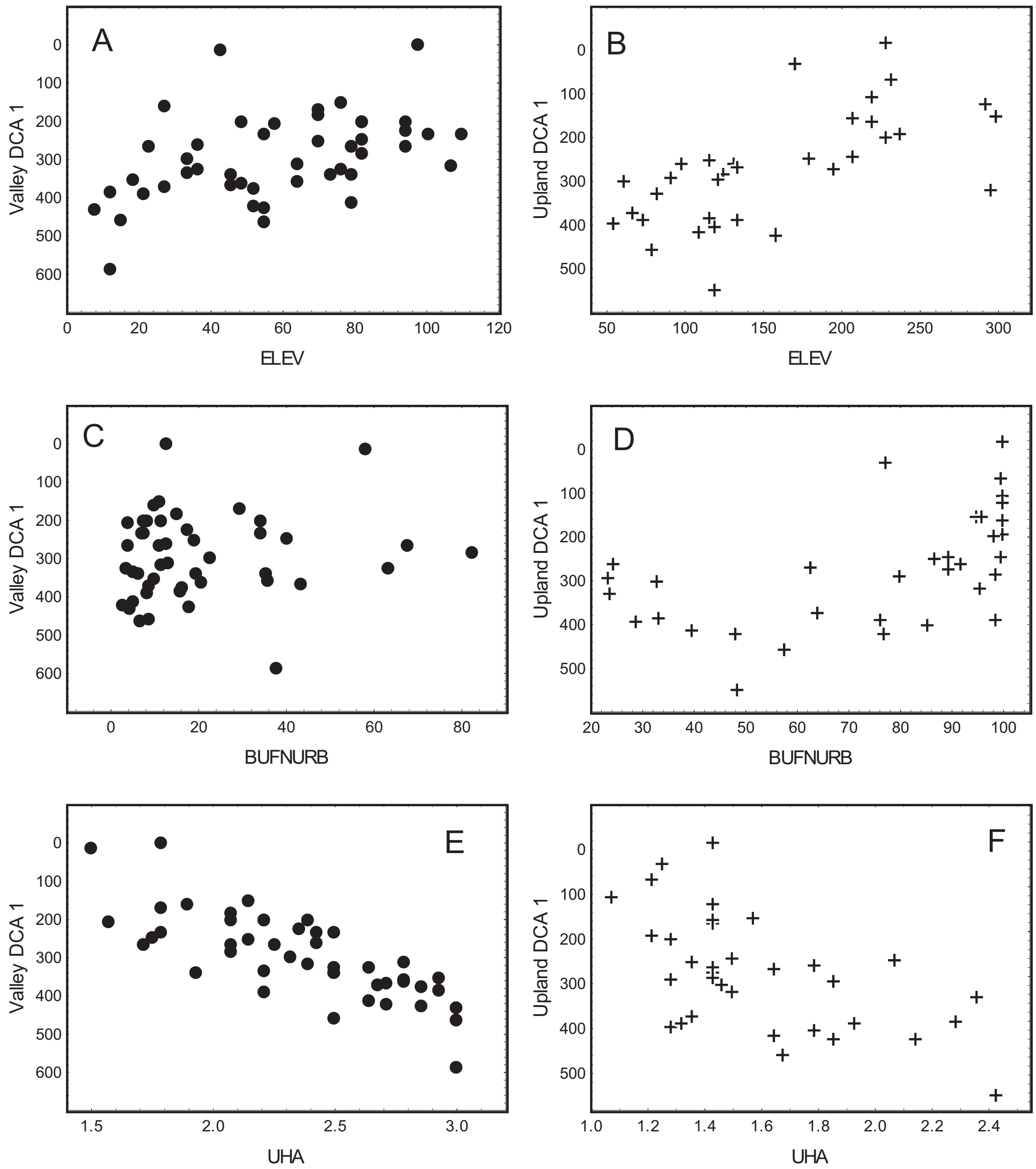
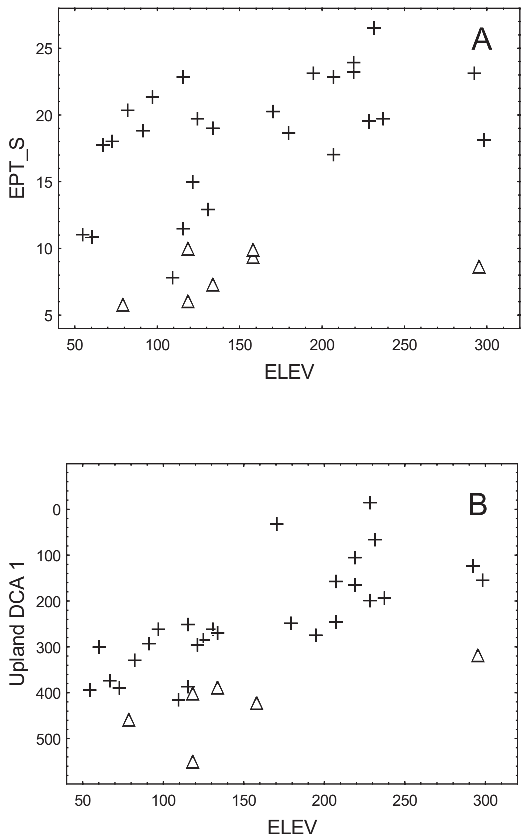


FIGURE 3. Plots of DCA 1 (axis 1 from a detrended correspondence analysis of macroinvertebrate data × 100) against habitat variables for valley (A, C, E) and upland (B, D, F) Santa Clara Valley site groups. Definitions of habitat variables: ELEV (site elevation in meters), BUFNURB (percent nonurban, nonagricultural land cover in 200 m by 2 km upstream buffers), and UHA (urban habitat index, see Table 2).

16th percentile (16%PS) or embeddedness (EMBED).

Field visual scores.—The combined VBHA index (VBTOT) was weakly correlated with macroinvertebrate scores, although some component metrics had higher correlations within one or more site groups (Table 4). Channel flow (VBCHFLO) was negatively correlated with site elevation, due to augmented flow below reservoirs during the low-flow sampling period. Consequently, this variable tended to increase with urbanization, and higher flow values were associated with poorer macroinvertebrate scores. Values for



FFGURE 4. Plots of macroinvertebrate variables against ELEV (site elevation in meters) for the Santa Clara Valley upland sites. Sites within 2 km of an upstream dam are indicated by triangles. Exclusion of sites within 2 km of an upstream dam increased the correlations (r_s) between elevation and EPT richness from 0.39 to 0.52, and DCA axis 1 from 0.66 to 0.84. Definitions of macroinvertebrate variables: EPT S (number of Ephemeroptera, Plecoptera, and Trichoptera taxa) and DCA 1 (axis 1 from a detrended correspondence analysis of macroinvertebrate data × 100).

riffle frequency (VBRIFFQ), riparian zone width VBRIPZW), and sediment deposition (VBSEDDP) were positively associated with macroinvertebrate scores.

The combined UHA index had relatively high correlations with the biological variables at the watershed scale and within the separate upland and valley site groups (Figures 2E, F, 3E, F). All component metrics (which increased with urbanization) were negatively correlated with macroinvertebrate measures. Habitat metrics related to channel modification (CHANMODF) and riparian condition and extent (RIPVEG, RIPW) were correlated with macroinvertebrates at the watershed scale and within the valley site group, where channels were most highly modified. Benthic silt (SILT) and turbidity (TURB) appeared more important within the upland site group. This presumably related to the downstream effects of dams, most of which were in the upland site group. The visual score for algal cover (ALGCOVR) was not included in the UHA, but was positively correlated with macroinvertebrate measures in the upland sites.

Discussion

Distribution of Macroinvertebrates in the SCV

The general responses of aquatic invertebrates to urban land use have been consistently documented in many regions and at different spatial scales. Even in the absence of obvious point sources or exceedances of water quality criteria, there is a general reduction in sensitive species such as EPT taxa, and increased dominance by a few widespread taxa, particularly Oligochaeta and Chironomidae (Klein 1979; Pratt et al. 1981; Duda et al. 1982; Pedersen and Perkins 1986; Jones and Clark 1988; Lenat and Crawford 1994; Kennen 1999; Walsh et al. 2001; Roy et al. 2003). Our results from the SCV are consistent with these expectations. Number of EPT taxa decreased with increasing urban land cover and habitat modification. The primary DCA axis, which could be interpreted as a trend from numerical dominance by EPT taxa to dominance by more tolerant taxa, was also correlated with measures of urbanization.

For the entire SCV watershed, benthic macroinvertebrate measures were equally associated with variables expressing natural gradients (elevation, slope, temperature) and urbanization effects (land cover and reach habitat quality). As in many other urbanizing watersheds, development is concentrated in lowland areas of the SCV and is inversely related to elevation and slope. Longitudinal patterns in stream biota have long been recognized (e.g., Hawkes 1975) and tend to dominate macroinvertebrate spatial distributions (e.g., Marchant et al. 1999). Thus, longitudinal patterns can be expected to have a confounding effect in many urbanization studies. Habitat variables related to longitudinal stream gradients (e.g., elevation, slope, temperature) often covary with measures of habitat impairment in macroinvertebrate surveys (Bargos et al. 1990; Tate and Heiny 1995; Carter et al. 1996; Robinson and Minshall 1998; Roy et al. 2003). Morley and Karr (2002) also noted an interaction between elevation and urban land use, even though their study was limited to a 5–140-m elevation range. Although they were able to partially control the problem by comparing two streams with different patterns of land use with respect to elevation, this amount of local variation in land use may not always be available. Cuffney et al. (2005, this volume) controlled known environmental factors such as elevation, while emphasizing a range of urbanization, but the process is complex, requires prior knowledge of natural gradients, and may severely limit spatial coverage in study areas with strong physical gradients.

The uniform arrangement of sample sites in our survey identified continuous relationships between biota and habitat characteristics from upper reaches through the valley floor in the SCV. However, although distinct strata were lacking, partitioning the watershed into upland and valley subsections indicated different habitat–macroinvertebrate relationships in different parts of the watershed. Reservoirs were a major anthropogenic effect on patterns within the upland site group. Downstream effects of reservoirs vary widely, depending on the relative modifications to flow regime, sediment supply, temperature regime, and/or trophic conditions (e.g., Stanford and Ward 1979; Ligon et al. 1995). Our categorical field observations and subsequent measurements of benthic fine sediments (Choy 2004) indicated an increase in fine sediment in the stream bed below the hypolimnetic-release reservoirs in the SCV. Increased fine sediment below dams has generally been attributed to the loss of seasonal flushing flows (Waters 1995), but our categorical observations of turbidity below dams in the SCV also suggested increased fine sediment supply under low-flow conditions. Reservoir effects may have been too localized to appear important in correlations at the scale of the entire watershed. The negative correlation of macroinvertebrate variables with DAMDIST in the valley site group can be attributed to the location of most dams in the upland part of the watershed; hence, DAMDIST is a surrogate for longitudinal position.

Because all of the valley sites (Santa Clara Valley subsection) were downstream of dams or experienced other forms of flow modification, effects of other habitat modifications were more apparent on the valley floor. Most valley sites had noticeably turbid water under low-flow conditions, most likely a result of combined effects of reservoir operation and urban land use (Jones and Clark 1988; Waters 1995). Because valley sites had a generally depauperate EPT assemblage compared with upland sites, macroinvertebrate response to measured habitat variables would likely be different. Within this setting, local channel and riparian habitat modification appeared to have a major effect on macroinvertebrate assemblages.

Evaluation of Habitat Variables

Landscape measurements.—Land cover determinations would appear the most direct and objective measures of urbanization, although even these measures include subjective elements, particularly when summarized as variables. Some land cover measures can indicate processes, such as the effect of watershed imperviousness on hydrology (Booth and Jackson 1997) and contaminant loads (Klein 1979; Jones and Clark 1988). Land-cover measures were more highly correlated with macroinvertebrates when the entire SCV watershed was analyzed than when the upland and valley site groups were analyzed separately, possibly because of the combined effects of interacting land use and natural gradients.

Landscape-scale processes are widely considered to constrain local habitat features (Frissell et al. 1986; Richards et al. 1997). Although it appears that aquatic macroinvertebrates can be reasonably well predicted by both large- and small-scale habitat observations (Carter et al. 1996; Roy et al. 2003; Townsend et al. 2003; Weigel et al. 2003), there is little consensus regarding the spatial scale at which aquatic systems respond to land cover. Studies in different settings have implicated measurements of reach conditions (Richards et al. 1997; Dovciak and Perry 2002; Townsend et al. 2003), upstream buffer strips (Sponseller et al. 2001; Morley and Karr 2002), and upstream subwatersheds (Wang et al. 1998; Kennen 1999), although Allan et al. (1997) suggested that results of such studies may depend on their spatial extent. In small, forested streams Sponseller et al. (2001) found that land cover was a better predictor of macroinvertebrate assemblages and water temperature when measured at a local scale (200 m corridor length) than when measured at larger spatial scales and cited other studies showing highly localized effects of riparian habitat on stream temperature and organic matter processing. Nevertheless, land cover measurements based on upstream buffer strips and subwatersheds were similarly correlated with macroinvertebrates in the SCV, except in the valley subregion. The better correlation with subwatershed measurements in the valley subregion should be interpreted with caution because headwaters of almost all streams were forested, and the gradually increasing percentage urban land cover in lower reaches may simply have been a surrogate for position in the drainage.

Differences in the association of land cover variables with macroinvertebrate measures in the SCV may relate more to imprecision of the available data than to differences in effects. The weaker association of PIA compared to percentage nonurban land cover may reflect imprecision in assigning imperviousness coefficients using NLCD. Road density was less highly correlated with macroinvertebrate scores, possibly because a large range of road types was given equal weighting. An additional problem in considering watershed effects is the lack of connectivity of urban streams to their topographically-defined watersheds (Short et al. 2005; this volume). Hydrologic modifications such as reservoir operation, interbasin transfers, storm drains, and withdrawals, combined with channelization, create difficulties in linking watershed processes to instream biotic responses in the SCV.

Booth and Jackson (1997) suggest that effects of imperviousness on lotic systems in urban areas are irreversible, and it is unlikely that large-scale changes in land use will be used to mitigate these effects. The most important questions may not relate to documentation of biotic responses to urbanization in general, but rather to identifying deviations due to local effects such as point sources, local habitat modifications, and runoff management. In this context, it may be useful to consider land cover as a background (predictive) variable rather than an "impairment" (Carter and Fend 2005, this volume). An alternative approach is to set lower criteria for sites in urbanized watersheds (Yoder and Rankin 1995).

Field measurements.—Field measurements were time-consuming relative to visual estimates of condition and, except for channel slope, had limited predictive value. In typical streams, dissolved constituents, particularly nutrients, should increase in a downstream direction (Hawkes 1975); dissolved constituents such as nutrients and metals also tend to increase with urbanization (Paul and Meyer 2001; Walsh et al. 2001). This general pattern occurred in the SCV, but correlations of these constituents with geomorphic, land use, and biological variables were low, most likely due to high variability in local sources. Principal components analysis results indicated that hypolimnetic water releases from reservoirs influenced longitudinal patterns in some constituents, and correlations of some chemical variables with macroinvertebrates within the upland site group suggested a macroinvertebrate response. Decreased pH and dissolved oxygen and high values of manganese and ammonia associated with some below-dam sites were presumably a consequence of altered redox conditions in the reservoir hypolimnion (Hannan 1979).

Sediment particle size and other microhabitat measurements had little predictive value, despite their importance in determining macroinvertebrate assemblage composition at smaller spatial scales (e.g., Minshall 1984). Some microhabitat effects (depth, velocity) were probably reduced by sampling only in riffle habitat. The better correlations with the largest particle size (*d*84) suggests that stability and/or local hydraulic habitat complexity may be more important than other sediment properties.

As in some other urban systems having impaired fauna (Duda et al. 1982; Walsh et al. 2001), chemical constituents in our limited samples generally did not approach concentrations expected to limit aquatic life. Low correlations of these and some other field measurements with biota could also imply that single measurements poorly represented rapidly changing discharge and water chemistry in these highly seasonal streams (Duda et al. 1982). However, most field measurements express components of a complex gradient, and the higher correlation of biota with elevation and land cover is presumably due to the combined effects of predictably covarying habitat characteristics, such as temperature regime and large-scale hydraulic environment (e.g., Hawkes 1975).

Field visual scores.—The macroinvertebrate variables were in some cases more highly correlated with field visual estimates than with land cover in the SCV, suggesting that rapid assessments are useful in accounting for local variation in biota caused by anthropogenic habitat modifications.

Components of the two habitat scoring systems were similar. However, the UHA was more highly correlated with biological variables than was the generic VBHA, indicating the value of adaptation to local conditions. On a smaller scale, differences in correlations between macroinvertebrate metrics and components of the UHA in the valley versus upland habitats of the SCV suggest that habitat assessments may need to be modified to account for particular influences.

Despite common use of macroinvertebrates in aquatic bioassessments, more of the literature on rapid habitat evaluation methods relates to fish habitat assessment. Results have been mixed, and studies have indicated regional variation in fish responses to habitat indices. Rankin (1995), working in Ohio, had greater success predicting fish metrics with a locally derived habitat index than with the VBHA and argued for regional adaptation of habitat evaluation methods. Wang et al. (1998) found observations of channelization, instream cover, and riparian habitat to be most useful in predicting fish index of biotic integrity scores in a statewide survey of low gradient streams in Wisconsin. In contrast, Hall et al. (2002) found that hydraulic complexity and sediment embeddedness distinguished reference from impaired sites in Maryland streams. Channel alteration and riparian buffer width did not appear important. In a Wisconsin study, Fitzpatrick et al. (2001) found that a Wisconsin habitat index was a better predictor of both fish and macroinvertebrate metrics than was a Michigan index. They attributed this to differences in the component habitat metrics, rather than to regional differences. The Michigan index emphasized local (instream) effects, whereas the Wisconsin index better represented riparian condition and was more highly correlated with other habitat measures, including land cover. Stauffer and Goldstein (1997) found that three rapid habitat approaches developed in other regions were of little use in predicting fish assemblages in prairie streams. Nevertheless, they proposed that careful selection of habitat metrics appropriate to the region could improve their predictive value.

Regional considerations may be important even if a habitat evaluation procedure is specifically developed for urbanization. For example, some processes commonly associated with urbanization, such as channel widening and downcutting, or increased runoff and sediment transport (Klein 1979), are greatly modified by flood-control engineering (channel enlargement and reservoir operations) in the SCV. The VBHA's emphasis on fluvial processes (erosion, sedimentation, and channel formation) may account for its poor performance in the highly controlled SCV streams. Visual-Based Habitat Assessment habitat metrics related to bank/channel stability were difficult to apply at sites with anthropogenically stabilized stream channels. Additionally, because decreased base flow may be expected in streams within impervious watersheds (Klein 1979), the metric "Channel Flow Status" positively weighted higher stream discharge. However, increased discharge may reflect anthropogenic modifications to the natural hydrograph of the SCV, a region with many intermittent streams having supplemented flows in their lower reaches. It is important to note that although the UHA provided information useful in interpreting macroinvertebrate distributions in the SCV, there is room for improvement. In addition to improving category definitions and optimizing scaling, further development of rapid habitat protocols for the SCV and urban systems in general might be gained by developing inexpensive measures for other stream attributes influenced by urbanization, such as habitat complexity and flow regime.

Because habitat effects on biota are location-dependent, it is difficult to make an a priori choice among potentially important habitat attributes. Consequently, habitat evaluations in biomonitoring protocols need to be comprehensive and express the range of conditions and modifications characteristic of the type of system in question; however, protocols must also be cost-effective. Petersen (1992) reported 20 min average time to complete a rapid habitat assessment protocol, which had many of the components of the VBHA. Our UHA procedure was a comparable effort, even with the limited measurements of embeddedness and canopy cover. Rapid habitat assessment protocols may be as efficient as more rigorous measurements in summarizing the complex channel information needed to describe some stream processes, and may be easier to apply at the scale of interest (reach, rather than a point or transect). For example, the category "channelized" may provide information equivalent to many measurements of bank angle, substrate, and riparian condition. At an exploratory or general monitoring stage, coarse observations of relevant environmental constraints are likely to be more useful than costly, precise measures of less-important habitat characteristics.

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